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Secular changes in the solar semidiurnal tide of the western North Atlantic Ocean

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[1] An analysis of twentieth century tide gauge records reveals that the solar semidiurnal tide S_2 has been decreasing in amplitude along the eastern coast of North America and at the mid-ocean site Bermuda. In relative terms the observed rates are unusually large, of order 10% per century. Periods of greatest change, however, are inconsistent among the stations, and roughly half the stations show increasing amplitude since the late 1990s. Excepting the Gulf of Maine, lunar tides are either static or slightly increasing in amplitude; a few stations show decreases. Large changes in solar, but not lunar, tides suggest causes related to variable radiational forcing, but the hypothesis is at present unproven. **Citation:** Ray, R. D. (2009), Secular changes in the solar semidiurnal tide of the western North Atlantic Ocean, *Geophys. Res. Lett.*, *36*, L19601, doi:10.1029/2009GL040217.

1. Introduction

[2] This work commenced as part of a broadened effort to understand some puzzling features of the tides in the Gulf of Maine. *Godin* [1995], following up earlier work by *Doodson* [1924], noticed that at St. John, New Brunswick, on the western shore of the Bay of Fundy, the amplitude of the M_2 tide is increasing by an unusually large rate, of order 10 cm century^{-1}, and further that S_2 is decreasing at roughly half that rate. By itself the phenomenon might be easily dismissed as a local curiosity, reflecting possibly some sort of environmental changes near the harbor, but the same secular changes were subsequently found to occur throughout the entire Bay of Fundy and Gulf of Maine system [*Ray*, 2006].

[3] As is well known, the tides of the Bay of Fundy are highly resonant and are therefore likely sensitive to small changes in basin geometry or depth. A plausible explanation for the tidal changes is a shift of the basin's fundamental resonance frequency away from S_2 toward M_2. But there are two serious objections to this explanation: (1) For the ocean to respond differently to forcing at such close frequencies ($30.00°\ h^{-1}$ and $28.98°\ h^{-1}$ for S_2 and M_2, respectively), and by amounts large enough to induce the observed changes, an unnaturally sharp (high Q) ocean resonance would be required. (2) Observations of tidal admittances as functions of frequency as well as numerical ocean modeling suggest that the Bay of Fundy resonance lies below the frequencies of M_2 and S_2 [*Garrett*, 1972, 1974], and not between them.

[4] To make progress it seems desirable to take a larger perspective, in part by testing for tidal changes over a larger region. Secular changes in tides are, in fact, not uncommonly detected when measurements over a long timespan are examined [*Cartwright*, 1972]. *Flick et al.* [2003] recently compiled statistics for rates in mean tidal range for 90 tide gauges in the United States, as *Woodworth et al.* [1991] had previously done for 13 British ports. More recently *Jay* [2009] analyzed tidal changes at 34 stations along the western coasts of North and South America and found secular trends in the M_2 and K_1 tides with surprisingly wide-scale coherence: all stations between Panama and Alaska showed increasing amplitudes, with an average increase of 2.2% per century.

[5] The present paper reports similar coherent trends for 12 stations along the boundary of the northwest Atlantic Ocean, plus one station (Bermuda) in the interior. In this case, however, attention is drawn to the solar constituent S_2, which is decreasing in amplitude at all 13 stations and by amounts significantly larger than the changes observed by Jay. Section 2 briefly describes our methods of analysis and presents the main findings. Implications for the curious tidal changes seen in the Gulf of Maine are addressed in Section 3. An obvious mechanism for large changes in solar, but not lunar, tides relates to radiational forcing and the atmospheric tide. This is discussed, somewhat inconclusively, in Section 4.

2. Observed Secular Tidal Trends

[6] Long time series of hourly data from thirteen stations (see Figure 1) form the basis for this work. The stations, all open directly to the sea, were selected based on the long lengths of their time series (as archived primarily at the University of Hawaii Sea Level Center). The time series at St. John's, Newfoundland, is 44 years long, much shorter than the others, but is included because it is the longest series in the western Atlantic Ocean north of 46°N. Key West is the southernmost station and is used even though all semidiurnal constituents there are small and it is somewhat blocked from the open Atlantic by the Bahamas. Bermuda is the only station with comparably long duration from the interior of the Atlantic Ocean; see *Wunsch* [1972] for more detailed discussion of its tides. The long (70 year) time series at Wilmington, North Carolina, is not used; *Flick et al.* [2003] found that its trend in mean tidal range is anomalously high—three times that of any other east coast station—but the station sits well up the Cape Fear River and is presumably reflecting very local tidal changes.

[7] From the hourly data amplitudes and phases of 43 tidal constituents (more at some stations) were estimated for each year having at least 7000 hourly observations. The estimation was done by least-squares harmonic analysis following standard methods, with one exception: In the

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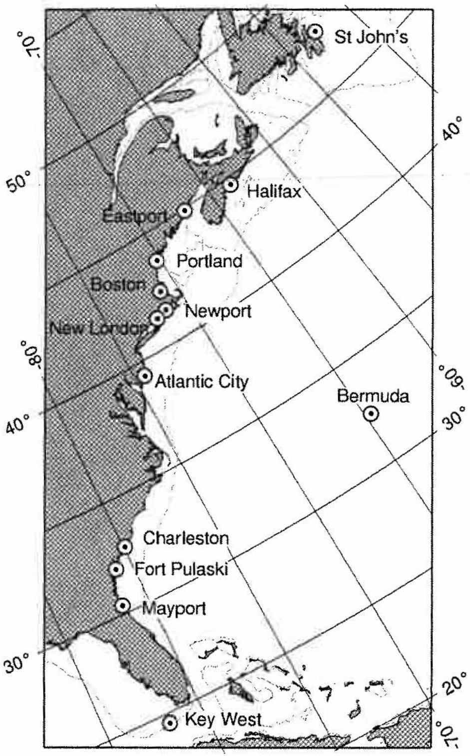

Figure 1. Tide gauge stations used in this study. The grey contour line is the 200-m isobath.

Gulf of Maine the 18.6-year nodal modulation of the M_2 tide is known to be smaller than its equilibrium value of ±3.7% because of frictional effects [*Ku et al.*, 1985]. For stations Eastport, Portland, and Boston, nodal modulations of ±2.3%, ±2.7%, and ±2.8%, respectively, were used, based on *Ray* [2006, Table 2]. For the other stations the equilibrium value appears to suffice.

[8] In the Atlantic Ocean diurnal tides are generally small; they never exceed 15 cm amplitude at our thirteen stations. It can be difficult to discern trends in small constituents in the face of estimation noise, so we focus on semidiurnal constituents, which are generally large in the Atlantic.

[9] The most striking results are found for the principal solar tide S_2. Figure 2 shows annual estimates of amplitude for each of the thirteen stations. Large secular trends (in both relative and absolute terms) are found to occur in amplitude, and these trends are negative (i.e., decreasing amplitude) at all stations. S_2 phase lags (not shown) are changing less markedly and are not completely consistent in sign among the stations (see Table 1). There is a slight tendency toward increasing phase lags.

[10] Although the overall S_2 amplitude trends are negative, Figure 2 shows that the periods of greatest change are not consistent among the stations. Many stations appear fairly constant during the early twentieth century, excepting a transient dip around 1920 at Portland, partly echoed at Boston and Halifax. In contrast, Newport shows a consistent drop since its beginning in 1931, while Charleston is fairly constant until 1980 and falls rapidly over the next two decades. Some amplitudes, including those in the Gulf of Maine which prompted this investigation, appear to have reversed direction around 1998 and have been increasing since then, although Newport and New London continue to fall.

[11] The northernmost (St. John's) and southernmost (Key West) stations display the smallest amplitude trends over the examined time period. The trend at St. John's is only marginally significant. Aside from a curious jump in 1928, Key West is remarkably flat until it begins to decay in 1985. The Bermuda time series appears somewhat confused until one realizes that the tide gauge was relocated several times: in 1939, 1944, and 1992 (see UHSLC documentation), marked by vertical lines in Figure 2. Allowing for these relocations, one sees that the amplitude at Bermuda has been decreasing over the entire timespan.

[12] Table 1 gives estimated linear trends (both absolute and relative to mean amplitude) for all stations over the seventy years 1935–2005, a period which seems to capture the times of greatest change over all stations. The tabulated standard errors on trends account for serial correlation by assuming an AR(1) noise process [*Lee and Lund*, 2004]. Similar statistics are also given in Table 1 for the principal lunar tide M_2. In contrast to S_2, M_2 shows increasing amplitude at most stations, but not consistently: three stations show a decrease and several show no significant change. (M_2 trends at Portland, Boston, and especially

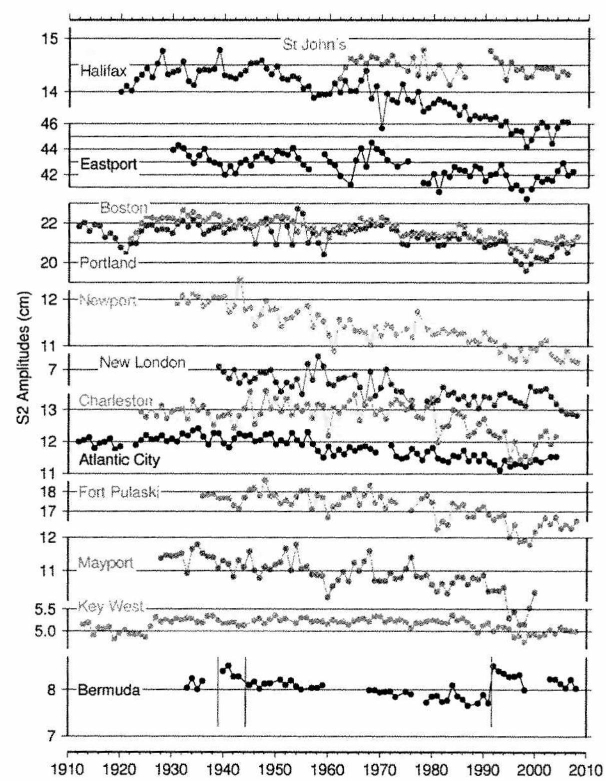

Figure 2. Annual estimates of the amplitudes of the S_2 tide at each of the 13 tide gauges. Standard errors for these estimates, based on spectral noise levels in the semidiurnal band, are typically around 0.2 cm, but are found to increase with amplitude, approaching about 0.5 cm for Eastport. Vertical lines on Bermuda series mark times when the tide gauge was relocated.

Table 1. Secular Trends in Amplitude H and Phase Lag G During 1935–2005

	M_2				S_2			
	H (cm)	ΔH (mm cy^{-1})	% ΔH (cy^{-1})	ΔG (° cy^{-1})	H (cm)	ΔH (mm cy^{-1})	% ΔH (cy^{-1})	ΔG (° cy^{-1})
St. John's[a]	35	−6 ± 4	−1.6 ± 1.2	−5.4 ± 5.0	14	−4 ± 2	−2.5 ± 1.2	−2.0 ± 5.4
Halifax	63	−24 ± 4	−3.7 ± 0.7	1.8 ± 0.8	14	−20 ± 1	−13.8 ± 0.9	4.4 ± 1.1
Eastport	264	75 ± 19	2.9 ± 0.7	−0.1 ± 1.6	43	−27 ± 8	−6.4 ± 2.0	2.8 ± 0.9
Portland	136	62 ± 10	4.4 ± 0.8	1.6 ± 0.9	21	−21 ± 5	−9.7 ± 2.3	5.8 ± 0.9
Boston	137	27 ± 9	2.0 ± 0.6	−0.7 ± 1.1	22	−19 ± 3	−8.6 ± 1.5	1.2 ± 1.0
Newport	51	−11 ± 3	−2.2 ± 0.7	1.2 ± 1.1	11	−16 ± 1	−14.4 ± 1.2	2.0 ± 1.3
New London	36	8 ± 2	2.1 ± 0.5	1.3 ± 1.2	7	−6 ± 1	−8.4 ± 1.3	0.8 ± 2.3
Atlantic City	59	0 ± 3	0.1 ± 0.5	2.0 ± 0.5	12	−14 ± 1	−12.4 ± 1.1	2.5 ± 0.9
Charleston	77	31 ± 25	4.0 ± 3.3	−3.8 ± 2.2	13	−16 ± 4	−12.1 ± 3.3	−2.1 ± 1.6
Fort Pulaski	100	23 ± 10	2.3 ± 1.0	1.1 ± 0.8	17	−26 ± 5	−15.1 ± 3.0	2.8 ± 1.0
Mayport	66	6 ± 15	0.9 ± 2.4	5.9 ± 1.3	11	−19 ± 4	−18.0 ± 3.8	7.2 ± 1.5
Key West	18	4 ± 2	2.2 ± 1.3	−3.4 ± 2.2	5	−4 ± 1	−7.8 ± 2.8	−3.6 ± 1.8
Bermuda[b]	36	1 ± 3	0.2 ± 1.0	0.7 ± 0.5	8	−12 ± 2	−15.8 ± 2.1	1.7 ± 0.7

[a]The St. John's time series is short; it begins in 1962.
[b]After adjustment for Bermuda station relocations.

Eastport are smaller than previously reported [*Ray*, 2006] owing to a different considered timespan; the previous trends were restricted to pre-1980 data.)

[13] Trends in N_2 (not shown) have characteristics similar to M_2. Amplitudes in the Gulf of Maine are increasing, Halifax is slightly decreasing, most others are flat or very slightly increasing. Charleston, however, is anomalous with a large relative increase of 7.4 ± 1.4 percent. Note that any analysis of N_2 must account for not only nodal modulations but also an 8.85-year oscillation in annual estimates induced by interference from the relatively large degree-3 N_2 tide.

[14] Table 1 emphasizes the unusual nature of the changes in S_2 amplitudes. Aside from being consistently negative, the magnitudes of these changes are large—the relative changes at all stations save St. John's exceed even the largest relative change seen in M_2. Moreover, the fact that similarly large S_2 decreases are occurring at Bermuda suggests that the changes may be basin-wide, throughout the entire western part of the North Atlantic. Unfortunately, no data are readily available to investigate the remainder of the central Atlantic. I have examined a few stations in the eastern Atlantic and found them to be inconsistent with the western Atlantic stations. In particular, S_2 at Newlyn, U.K., shows a barely positive trend of +0.50 ± 0.43 percent since 1935 (somewhat larger if 1915–1935 data are included).

[15] It is worth noting that these observed secular trends in amplitudes are unrelated to the much smaller secular changes in the astronomical tidal potential. Owing to the earth's decreasing obliquity, most semidiurnal equilibrium tides are slowly increasing (K_2, being a declinational tide, is an exception). The present-day change in the S_2 potential is roughly 0.01% cy^{-1} [*Cartwright and Edden*, 1973], insignificant in comparison with our Table 1 changes.

3. Implications for Gulf of Maine

[16] Tides in the Gulf of Maine are driven primarily by the ocean tide at its mouth, not directly by the tidal potential. Thus, to study the Gulf of Maine resonance and its response (or admittance) as a function of frequency, we should form admittances with respect to the observed tide at, say, Halifax [e.g., *Garrett*, 1972].

[17] Figure 3 shows annual estimates of admittance at Eastport relative to the observed tide at Halifax. Although the N_2 and S_2 error bars are large, we can nonetheless discern clear trends of increasing admittances at all three tidal frequencies. Similar results are found for other stations in the gulf. Thus, the mystery alluded to in the Introduction is solved: S_2 amplitudes are decreasing in the Gulf of Maine only because of decreasing amplitudes at the mouth. In fact, the gulf's tidal response is increasing at all frequencies across the semidiurnal band. Whatever resonance characteristics are changing within the Gulf of Maine, they result in magnified tides across the whole semidiurnal spectrum, as one would normally expect of an ocean resonance.

4. Causes of Basin-Scale Changes in S_2

[18] Yet we have replaced one mystery with another. If the S_2 decreases in the Gulf of Maine simply reflect reduced

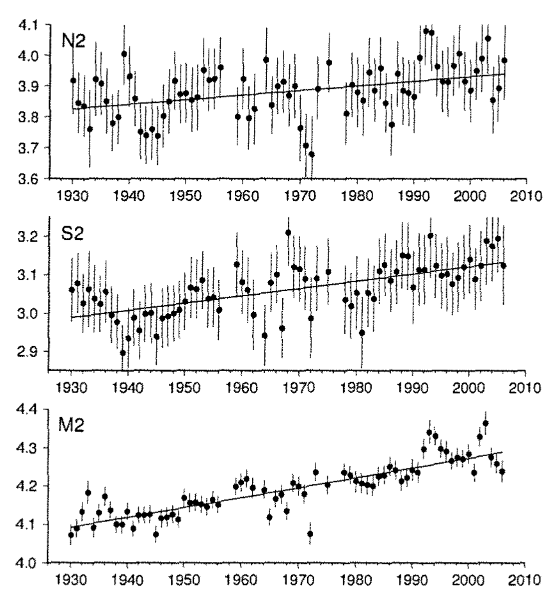

Figure 3. Annual estimates of admittance magnitudes of the N_2, S_2, and M_2 tides at Eastport, relative to the observed tides at Halifax. Linear fits to each time series show that the admittance inside the Gulf of Maine system is increasing for all three constituents.

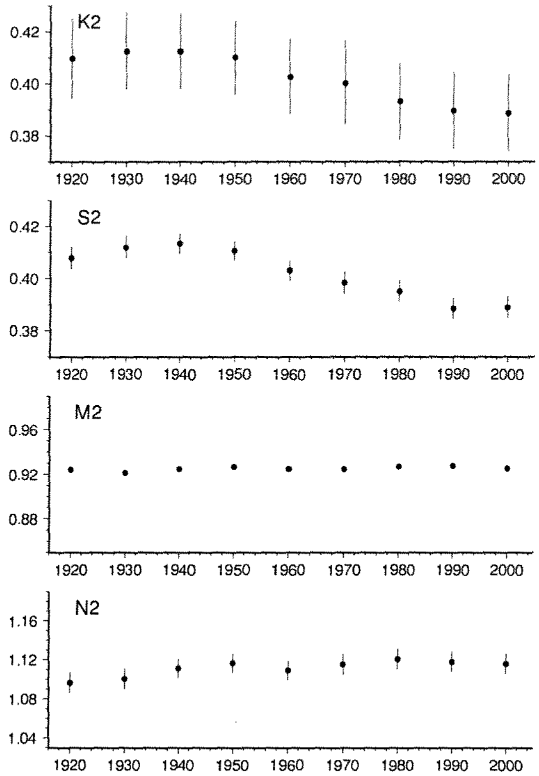

Figure 4. Admittance magnitudes at Atlantic City relative to the astronomical potential, estimated every 10 years in overlapping 18.6-y windows. For each constituent the range of vertical axis is 15% of the mean admittance; this emphasizes the relatively constant natures of the lunar M_2 and N_2 tides while the solar S_2 and luni-solar K_2 are both decreasing rapidly since 1940.

S_2 forcing at its opening to the Atlantic, what is the cause of *those* decreases?

[19] We emphasize that the S_2 changes are proportionally far larger than the changes seen in M_2 or N_2 and far larger than the trends reported in M_2 and K_1 by *Jay* [2009]. One rather obvious explanation for anomalous basin-scale changes in a solar, but not lunar, tide involves changes in its radiational component, that part of the tide driven not by the astronomical potential but rather by pressure loading of the ocean by the corresponding atmospheric tide.

[20] There have been occasional reports of secular changes in the S_2 atmospheric tide, which could in part owe to climatic changes in stratospheric ozone (one of the primary insolation sinks for exciting S_2) or to changes in upper atmospheric winds or temperatures. *Hamilton* [1984] noted some long-terms trends in the S_2 air tide at Jakarta, Indonesia (his series unfortunately stops in 1944 so does not overlap well with our series). *Bartzokas et al.* [1995] report a 0.5-hour drift in the S_2 tidal phase at Athens, Greece, over the course of the twentieth century. It is worth noting that if the ocean tide changes reported here stem in part from changes in the atmospheric tide, the latter need not be confined to the North Atlantic; owing to the ocean's highly dynamic response at the S_2 frequency, large air-tide changes almost anywhere could be responsible.

[21] There are, however, several difficulties with an air-tide explanation. Firstly, the mean global radiational component of S_2 is only about 10% [*Cartwright and Ray*, 1994]. To obtain a 10% change in the ocean S_2 (Table 1) would thus require a very large relative change in the S_2 air tide. On the other hand, many locations exceed the 10% global mean. *Zetler* [1971] reported values along the U.S. coasts between 6–32% (the highest was at Eastport). Using a well-tuned numerical model, *Arbic* [2005] found the radiational-to-gravitational ratio along the U.S. east coast to be roughly 20%, larger than almost anywhere else in the Atlantic Ocean. So the northwest Atlantic may be unusually sensitive to changes in radiational forcing.

[22] A second difficulty is that similar amplitude changes evidently occur in K_2. Trends are more difficult to discern for K_2 because of noise levels, but they emerge clearly when extracting tidal estimates from longer, multi-year segments. Figure 4 shows overlapping 18.6-year admittance estimates (now relative to the generating potential) of the four largest semidiurnal tides at Atlantic City. The changes in K_2 are almost lock-step with those in S_2. Yet the radiational component of K_2 is much smaller than that of S_2. For example, from an (unpublished) analysis of air tides at St. Helena (16°S, 6°W) we find the ratio of K_2 to S_2 amplitudes is (0.076 mb)/(1.096 mb), or 0.07, while the ratio of their gravitational potentials is 0.27. It is difficult to see how such a small radiational contribution could have such a large effect on K_2.

[23] In light of these difficulties, attributing observed S_2 changes to a variable radiational component seems premature, and may well be incorrect. But it does suggest that further scrutiny of historical meteorological records would be a timely endeavor.

[24] **Acknowledgments.** Work of this kind owes immeasurably to generations of anonymous tide-gauge operators. Their sea-level records have been refined, compiled, and archived by the University of Hawaii Sea Level Center and the British Oceanographic Data Centre, from which I obtained the hourly data used here. It is a pleasure to thank David Cartwright, Chris Garrett, Florent Lyard and Philip Woodworth for useful suggestions. This work was supported by the NASA Ocean Surface Topography program.

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